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Mailing Label No. EL 915821435 US

Date of Deposit: 8-8, 2001

# **USING SISO DECODER FEEDBACK TO PRODUCE SYMBOL PROBABILITIES FOR USE IN WIRELESS COMMUNICATIONS THAT UTILIZE TURBO CODING AND TRANSMIT DIVERSITY**

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This application claims the priority under 35 USC 119(e)(1) of copending U.S. provisional application number 60/227 094 filed on August 22, 2000.

## **FIELD OF THE INVENTION**

The invention relates generally to wireless communications and, more particularly, to wireless communications that utilize turbo coding and transmit diversity.

## **BACKGROUND OF THE INVENTION**

Each of the documents listed below is referred to herein by the corresponding number enclosed in square brackets to the left of the document. Each of these documents is also incorporated herein by reference.

- 15 [1] Y. Liu, M. P. Fitz, and O. Y. Takeshita, "Qpsk space-time turbo codes," in *IEEE ICC*, June 2000.
- [2] X. Li and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding," using soft feedback, " *Electronic Letters*,, vol. 34, pp. 942-943, 4 March 1998.
- 20 [3] X. Li and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding," in *IEEE ICC*, vol. 2, pp. 858-863, June 1999.

- [4] X. Li and J. A. Ritcey, "Trellis-coded modulation with bit interleaving and iterative decoding," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 715-724, April 1999.
- [5] X. Li and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding," *IEEE Communications Letters*, vol. 1, pp. 169-171, November 1997.

Coding and interleaving techniques are often used in wireless communication systems to improve the communication performance. FIGURE 1 illustrates an example of a conventional wireless communication system described in [1]. This example implements turbo coding by using two convolutional coders (CC). One of the convolutional coders receives at its input the data stream that is to be transmitted, and the other convolutional coder receives at its input an interleaved (see 10) version of the data stream. The outputs of the convolutional coders are then modulated using QPSK (Quadrature Phase Shift Keying) and transmitted by respective transmit antennas. At the receiver, the signal from the antenna is input to a probability generator which generates symbol (or bit) probabilities. These symbol probabilities are fed to soft-input, soft-output (SISO) decoders that iterate to get estimates of the transmitted symbols (or bits). The SISO decoders use knowledge of the trellis of the convolutional coders to produce the estimates.

FIGURE 2 illustrates an example of a conventional wireless communication system described in [2] and [3]. The system of FIGURE 2 uses a single convolutional coder and an interleaver 21 before modulation and transmission by a single antenna. At

the receiver, the signal from the antenna is demodulated and de-interleaved (see 22), and is then input to a SISO decoder. The a posteriori symbol probabilities output from the SISO decoder are interleaved (see 23) and fed back into the demodulator to get a better estimate of the symbol probabilities. This loop is iterated over. Systems similar to the one illustrated in FIGURE 2 have also been suggested in [4] and [5], but those systems implement hard decoding decisions instead of soft decisions.

It is desirable in view of the foregoing to provide for improved performance in wireless communication systems that utilize turbo coding and transmit diversity.

According to the invention, in a wireless communication system with transmit diversity, a posteriori probabilities from a SISO decoder are fed back to the symbol probability generator, thereby advantageously permitting the symbol probability generator to produce an improved estimate of the received symbols.

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**BRIEF DESCRIPTION OF THE DRAWINGS:**

FIGURE 1 illustrates a conventional wireless communication system which utilizes interleaving, turbo coding and transmit diversity.

FIGURE 2 illustrates a conventional wireless communication system that utilizes  
5 turbo coding, interleaving and feedback of a posteriori probabilities from a SISO decoder.

FIGURE 3 diagrammatically illustrates exemplary embodiments of wireless communication systems which utilize turbo coding, interleaving, transmit diversity and a posteriori probability feedback according to the invention.

FIGURE 4 diagrammatically illustrates exemplary embodiments of the  
10 probability generator of FIGURE 3.

FIGURE 5 illustrates exemplary operations which can be performed by the receiver of FIGURE 3.

FIGURE 6 diagrammatically illustrates further exemplary embodiments of wireless communication systems which utilize interleaving, turbo coding, transmit  
15 diversity and a posteriori probability feedback according to the invention.

FIGURE 7 illustrates exemplary simulation results for the systems of FIGURES 1, 3 and 6.

## DETAILED DESCRIPTION

Referring again to FIGURE 1, the symbol  $Z_t$  received by the antenna of the receiver 12 at time  $t$  can be expressed as a function of the corresponding symbols or bits  $X_t$  and  $Y_t$  produced by the respective convolutional coders of the transmitter 11, and the fading characteristics of the respective wireless communication channels through which  $X_t$  and  $Y_t$  are transmitted to the receiver 12. The fading characteristics (or coefficients) are illustrated by fading parameters  $\alpha$  and  $\beta$  in FIGURE 1. Accordingly, the symbol value received by the antenna of the receiver 12 can be expressed as follows

$$Z_t = \alpha X_t + \beta Y_t + n_t, \quad (1)$$

where  $n_t$  represents noise in the wireless communication channels. At 13, the probability generator 15 produces, for all possible values  $C_X$  that  $X_t$  can assume at time  $t$ , the following probability

$$P(X_t = C_X | Z_t = C_Z) \quad (2)$$

Expression (2) above represents the probability that  $X_t = C_X$  given that the received symbol or bit value  $Z_t = C_Z$ . At 14, the probability generator 15 produces similar probabilities for all possible values  $C_Y$  of  $Y_t$ , namely

$$P(Y_t = C_Y | Z_t = C_Z) \quad (3)$$

Taking the probability defined in Expression (2) above as an example, and applying Bayes' Rule, Expression (2) can be written as follows

$$P(Z_t = C_Z | X_t = C_X) P(X_t = C_X) / P(Z_t = C_Z) \quad (4)$$

In practice, for an iterative loop, the probability given by Expression (2) is generated under the assumption that nothing is known in advance about the statistics of  $X_t$ . This is called the extrinsic probability and ensures that only “new” information is used to generate data that will be fed back. Therefore,  $P(X_t = C_x)$  can be eliminated from  
 5 Expression (4). The denominator of Expression (4) can also be eliminated because it merely represents the probability that  $Z_t = C_z$  at time  $t$ , which is merely a constant value that operates only as a scaling factor. Thus, eliminating the aforementioned extrinsic factor and the aforementioned scaling factor from Expression (4) leaves

$$P(Z_t = C_z | X_t = C_x) \quad (5)$$

10 Using known probability theory, Expression (5) can be rewritten as follows

$$\sum_{C_y} P(Z_t = C_z | X_t = C_x \text{ and } Y_t = C_y) P(Y_t = C_y | X_t = C_x) \quad (6)$$

Referring again to Equation (1) above, the leftmost probability of Expression (6) can be rewritten as follows

$$P(n_t = C_z - \alpha C_x - \beta C_y) \quad (7)$$

15 Substituting Expression (7) into Expression (6) gives

$$\sum_{C_y} P(n_t = C_z - \alpha C_x - \beta C_y) P(Y_t = C_y | X_t = C_x) \quad (8)$$

Thus, Expression (2) above can be rewritten as Expression (8) above.

The noise  $n_t$  in Expression 8 can be modeled as a Gaussian random variable, and the fading parameters  $\alpha$  and  $\beta$  can be readily estimated. Thus, given that the received  
 20 symbol  $Z_t = C_z$  is known, values of the leftmost probability in Expression 8 can be easily

calculated for all possible values of  $C_X$  and  $C_Y$ . The values of the rightmost probability of Expression (8) are provided according to the invention as the a posteriori output probabilities from a SISO decoder, as described in more detail below.

Using reasoning analogous to that given above for rewriting Expression (2) as  
 5 Expression (8), Expression (3) above can be rewritten as follows

$$\sum_{C_X} P(n_t = C_Z - \alpha C_X - \beta C_Y) P(X_t = C_X | Y_t = C_Y) \quad (9)$$

As mentioned above with respect to Expression (8), the leftmost probability of Expression (9) can be easily calculated for a known value of  $C_Z$  and all possible values of  $C_X$  and  $C_Y$ . Also analogous to the discussion of Expression (8) above, the values of the  
 10 rightmost probability of Expression (9) are provided according to the invention as a posteriori output probabilities of a SISO decoder.

Referring now to FIGURE 3, in exemplary wireless communication system embodiments according to the invention, a receiver 31 includes a probability generator 34 coupled to an antenna which receives symbol  $Z_t$  from a transmitter that employs transmit  
 15 diversity, for example the transmitter 11 of FIGURE 1. The probability generator 34 calculates the values of the leftmost probability in Expressions (8) and (9). At its input 47, the probability generator receives (as feedback) from SISO decoder 35 the values of the rightmost probability of Expression (9). At its input 48, the probability generator 34 receives (as feedback) from the SISO decoder 36 the values of the rightmost probability  
 20 of Expression (8). Having calculated the values of the leftmost probability of Expressions (8) and (9), and having received the values of the rightmost probabilities of

Expressions (8) and (9) from the SISO decoders 36 and 35, respectively, the probability generator 34 performs the summation of Expression (8) to produce at its output 45 the values of the probability of Expression (2), and also performs the summation of Expression (9) to produce at its output 46 the values of the probability of Expression (3).

5 The outputs 45 and 46 provide a priori output probabilities to the SISO decoders 35 and 36. The decoder 35 operates with respect to  $X_t$  and the decoder 36 operates with respect to  $Y_t$ . The SISO decoders 35 and 36 use their respective a priori output probabilities to produce respective a posteriori input probabilities. The a posteriori input probabilities produced by SISO decoder 35 are interleaved at 38 (corresponding to the  
10 interleaver in the transmitter 11) and the results are provided as a priori input probabilities to the SISO decoder 36. Similarly, the a posteriori input probabilities produced by the SISO decoder 36 are de-interleaved at 37 (again corresponding to the interleaver of the transmitter 11) and the results are provided as a priori input probabilities to the SISO decoder 35. The a posteriori input probabilities produced by the  
15 SISO decoder 35 are also provided to a decision maker which can use conventional techniques to decide the input symbol (as seen by the corresponding coder 16) based on the a posteriori input probabilities.

The output probabilities provided to (a priori) and produced by (a posteriori) the SISO decoder 35 represent respective probabilities that the symbol  $X_t$  as output from the  
20 convolutional coder 16 has respective ones of a plurality of possible values. Similarly, the input probabilities provided to (a priori) and produced by (a posteriori) SISO decoder 35 represent respective probabilities that the symbol that was input to the convolutional



coder 16 to produce  $X_t$  has respective ones of a plurality of possible values. The SISO decoder 36 functions analogously with respect to the symbol  $Y_t$  and the convolutional coder 17. Each SISO decoder uses the a priori probabilities (input and output) provided thereto together with knowledge of the trellis used by the corresponding convolutional  
 5 coder to produce corresponding a posteriori probabilities (output and input). In some embodiments, each coder 16 and 17 uses the same trellis.

FIGURE 4 diagrammatically illustrates exemplary embodiments of the probability generator 34 of FIGURE 3. A fading parameter estimator 42 provides estimates  $\alpha'$  and  $\beta'$  of the fading parameters  $\alpha$  and  $\beta$  of FIGURE 3 using, for example,  
 10 any desired conventional technique. A calculation apparatus 41 receives these estimated fading parameters, and also has access (e.g. from look-up table values) to the noise parameter  $n_t$ , which can be modeled, for example, as a Gaussian random variable. The calculation apparatus 41 knows the value of  $C_z$  (simply the received value) in Expressions (8) and (9), and thus can calculate the values of the leftmost probability in  
 15 Expressions (8) and (9) using the estimated fading parameters  $\alpha'$  and  $\beta'$ . Thus, the calculation apparatus 41 produces at 49 the values of the leftmost probability of Expressions (8) and (9). These values are input to combiners 43 and 44.

The combiner 43 receives at 47 the a posteriori output probabilities produced by SISO decoder 35, and the combiner 44 receives at 48 the a posteriori output probabilities  
 20 produced by SISO decoder 36. The values received at 47 represent the values of the rightmost probability in Expression (9) and the values received at 48 represent the values of the rightmost probability in Expression (8). The combiner 43 operates to combine the

values that it receives at 49 and 47 in the manner shown in Expression (8), namely multiplying the values together and summing the resulting products over all possible values of  $C_Y$ . Similarly, the combiner 44 combines the values that it receives at 49 and 48 as shown by Expression (9) above, namely multiplying the values together and summing the resulting products over all possible values of  $C_X$ . The combiner 43 produces at 46 the values of the probability shown in Expression (3), and the combiner 44 produces at 45 the values of the probability shown in Expression (2).

It should be clear that the probability generator 34 can easily account for the scaling factor described above with respect to Expression (4) by suitably normalizing the probability values that it generates, although such normalizing is not explicitly shown in the drawings.

FIGURE 5 illustrates exemplary operations which can be performed by the receiver embodiments of FIGURES 3 and 4. At 51, initial a priori output probabilities are produced for the SISO decoders. This can be done, for example, by the probability generator 34 calculating the values of the leftmost probabilities of Expressions (8) and (9) and summing these values without multiplying by the rightmost probabilities of Expressions (8) and (9) (which rightmost probabilities are not yet available as feedback from the SISOs). FIGURE 5 assumes that the SISO decoder 35 is selected to operate first and begin the iterative process. However, the SISO 36 could also be selected to operate first and begin the iterative process, and this possibility is therefore indicated by the parenthetical expressions in FIGURE 5. The following textual description of FIGURE 5 assumes the aforementioned example of beginning with SISO 35.

At 52, SISO 35 uses the initial a priori output probabilities to produce a posteriori input probabilities. At 53, interleaving is applied to the a posteriori input probabilities from SISO 35. At 54, SISO 36 uses the initial (for the first iteration) a priori output probabilities and the interleaved a posteriori input probabilities of SISO 35 to produce a posteriori input and output probabilities. At 55, de-interleaving is applied to the a posteriori input probabilities from SISO 36. At 56, the a posteriori output probabilities from SISO 36 are used to produce a priori output probabilities for SISO 35. At 57, the SISO 35 uses its a priori output probabilities and the de-interleaved a posteriori input probabilities of SISO 36 to produce a posteriori input and output probabilities. At 58, the a posteriori output probabilities from SISO 35 are used to produce a priori output probabilities for SISO 36. The operations at 53-58 are then repeated for any desired number of iterations.

FIGURE 6 diagrammatically illustrates further exemplary embodiments of a wireless communication system according to the invention. In the system of FIGURE 6, the transmitter 61 is similar to the transmitter 11 of FIGURES 1 and 3, but includes interleavers 63 and 64 at the outputs of the convolutional coders. Thus, the receiver 62 includes a de-interleaver 65 and an interleaver 66 to account for the operations of the interleaver 63, and also includes a de-interleaver 67 and an interleaver 68 to account for the operation of the interleaver 64. Aside from the operations of the interleavers and de-interleavers illustrated at 63-68, the wireless communication system of FIGURE 6 can operate in generally the same fashion as the wireless communication system of FIGURE 3, that is, generally as described above with respect to FIGURE 5.

FIGURE 7 illustrates exemplary simulation results for the systems of FIGURE 1 (71), FIGURE 3 (72), and FIGURE 6 (73). As shown in FIGURE 7, the FIGURE 3 system at 72 performs better (in terms of frame error rate FER) than the FIGURE 1 system at 71, showing gains of about 2 dB at higher SNRs. The FIGURE 3 system also exhibits a noticeable increase in slope, so the gains can be expected to be even larger at higher SNRs. The FIGURE 6 system at 73 provides an additional performance gain of about 1 dB at the higher SNRs, and also exhibits an increase in slope as compared to the system of FIGURE 1 at 71.

It will be apparent to workers in the art that any wireless communication system that utilizes a space-time turbo code, or any kind of turbo code, can benefit from the present invention. Advantageously, the added complexity of the a posteriori output probability feedback loops is relatively small compared to the complexity of a SISO block. It will also be apparent to workers in the art that the embodiments of FIGURES 3-6 can be implemented, for example, by suitable modifications in hardware, software, or a combination of hardware and software, in conventional wireless communication transmitters and receivers.

Although exemplary embodiments of the invention are described above in detail, this does not limit the scope of the invention, which can be practiced in a variety of embodiments.